MICROSYSTEMS, INSTRUMENT ELECTRONICS, AND MOBILE SENSOR PLATFORMS

G. W. Hunter(1), R. S. Okojie(2), L. Oberle(3), M. Krasowski(4), G. M. Beheim(5), G. Fralick(6), J. Wrbanek(7), P. Greenberg(8), P. G. Neudeck(9), and J. Xu(10).

(1)NASA Glenn Research Center at Lewis Field, 21000 Brookpark Road, Cleveland, OH 44135, USA, Email: Gary.W.Hunter@nasa.gov
(2)Email: Robert.S.Okojie@grc.nasa.gov, (3)Email: Lawrence.G.Oberle@nasa.gov,
(4)Email:Michael.J.Krasowski@nasa.gov, (5)Email: Glenn.M.Beheim@nasa.gov,
(6)Email: Gustave.C.Fralick@nasa.gov, (7)Email: John.D.Wrbanek@nasa.gov,(8)Email: Paul.S.Greenberg@nasa.gov,
(9)Email: Neudeck@nasa.gov, (10)Email: Jennifer.Xu@nasa.gov

ABSTRACT

NASA Glenn Research Center is presently developing and applying a range of sensor and electronic technologies that can enable future planetary missions. These include space qualified instruments and electronics, high temperature sensors for Venus missions, mobile sensor platforms, and microsystems for detection of a range of chemical species and particulates. A discussion of each technology area and its level of maturity is given.

1. INTRODUCTION

NASA Glenn Research Center (GRC) is presently developing and applying a range of sensor and electronic technologies that, while initially developed for other applications, can enable future planetary missions. NASA GRC has extensive experience in space qualified electronics integrated with instrument systems. This experience ranges from the Material Adherence Experiment (MAE), which flew on the Mars Pathfinder Sojourner in 1996, to the recent Materials International Space Station Experiment 5 (MISSE-5) Forward Technology Solar Cell Experiment. World-leading development in harsh environment sensors and electronics is also on-going and uniquely positioned to contribute to future Venus missions. While the high temperature electronics capability is covered in another paper at this conference [1], this paper discusses in more detail a wide range of Microsystems based sensor technology for in-situ Venus measurement applications. Mobile sensor platforms are also being developed for sensor placement, as well as methods for communicating between roving platforms and a central command location. This work leverages commercially available equipment to miniaturize existing sensor platforms and produce mobile platforms that are compatible for planetary exploration. Finally, a range of Microsystems based sensors have also been developed for applications such as fire detection, leak detection, EVA, and environmental monitoring. These microsystems also have applications in planetary exploration missions.

The purpose of this paper is to describe the various microsystems, instrument electronics, high temperature sensors, and mobile sensor platforms available at NASA GRC and their possible application in planetary exploration applications.

2. SPACE QUALIFIED ELECTRONICS

NASA GRC has extensive experience in space qualified electronics integrated with instrument systems. The focus of this group's activity has been specialized in choosing parts and designing space qualified electronics systems based on commercial-off-the-shelf (COTS) electronics and integrating these systems with a range of instrumentation. These resulting electronics/instrument units are stand-alone systems with appropriate interfaces to be integrated with the rest of the flight system. A standard design feature is the assurance that failure of the instrument unit does not affect operation of other experiments or systems. Other design issues vary with the application, but include minimal power consumption and mass, as well as operation in space radiation environments. The following are examples of these space qualified electronics systems and associated instrumentation whose development and operation span over a decade.

The Material Adherence Experiment (MAE) flew on the Mars Pathfinder Sojourner in 1996 and measured the effects of dust on the rover's solar panel (Fig. 1). MAE, composed both of electronics and a corresponding dust measuring instrument, functioned in the harsh thermal and radiation surface environment on Mars. The sensor saturated early in the mission during a secondary egress attempt for the rover, but during the mission the electronics continued to operate as required by mission parameters.

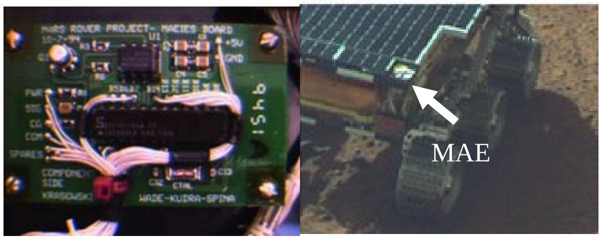

Fig. 1. The MAE circuit board and the location of the MAE on the Pathfinder Sojourner solar panel.

The Mars Array Technology Experiment (MATE) and Dust Accumulation and Removal Technology (DART) experiment were designed and qualified for the 2001 Surveyor Lander Mars In-Situ Propellant Precursor mission (Fig. 2). MATE and DART had an array of instruments for characterizing the solar and dust environment on Mars. This included sun position sensors, two radiometers, a microscope, visible and near infrared spectrometers, and a myriad of dust mitigation experiments. While the mission was cancelled, the MATE and DART design and qualification significantly broadened this group's experience in electronics and instrument design for planetary missions.

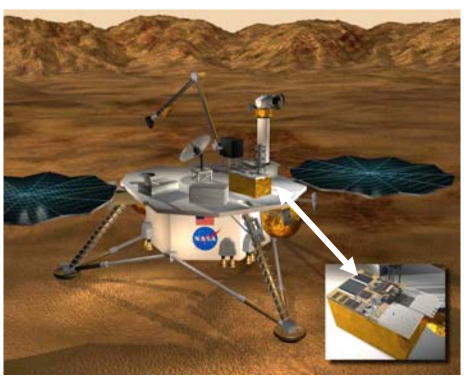

Fig. 2. The location of MATE and DART on the Mars Surveyor Lander

Most recently, this group took the radiation tolerant microprocessor core from MATE and DART and produced the Materials International Space Station Experiment 5 (MISSE-5) Forward Technology Solar Cell Experiment (FTSCE) (Fig. 3). FTSCE is currently operating successfully while mounted external to the International Space Station, exposed to the Low Earth Orbital environment on a nominal one year mission. This system operates autonomously or as directed by ground link from the U.S. Naval Research Labs. Data is archived on-board along with scheduled dumps to Earth receivers. It is designed to last for 2.4 years if its removal EVA is delayed for any reason. FTSCE is comprised of the core electronics board and nine data acquisition boards each displacing 75 cubic centimeters. Each is capable of interrogating numerous sensors and has been successfully sending data to Earth since its insertion on Aug. 3, 2005. Neither data corruption nor interruption of operations has occurred despite high radiation fluence from solar flare activity.

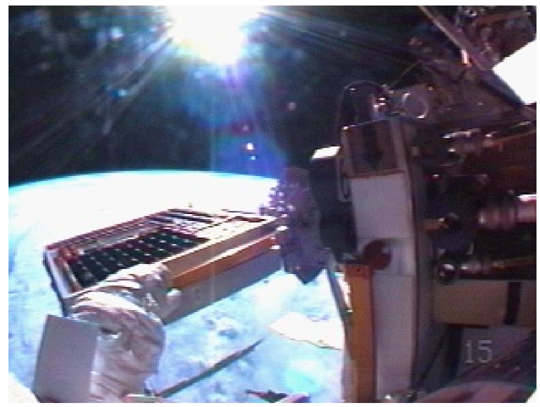

Fig. 3. The FTSCE experiment container being installed on the P6 solar panel strut on the ISS.

These activities demonstrate the capability to provide space qualified electronics capable of interfacing with a wide range of instrumentation. These space qualified electronics have been designed, qualified, and, in some cases, demonstrated operation in environments ranging from in-space to planetary. The need for space qualified electronics is prevalent across all planetary missions and is a prerequisite of a successful operational system. NASA GRC has the capability to provide such electronics for planetary exploration consistently on-schedule and on-budget.

3. HARSH ENVIRONMENT SENSOR TECHNOLOGY DEVELOPMENT

A range of sensor development applicable to Venus missions is on-going at NASA GRC. While related high temperature electronics work and application of sensors and electronics to a Venus Integrated Weather Sensor (VIWS) System is described in another paper in the workshop [1], this paper provides details on the high temperature sensors which can provide measurements in extreme environments. The sensor development includes pressure sensors, thin film sensors, and chemical sensors [2]. Each of these sensor types will be described in the subsections that follow.

3.1 High Temperature SiC Pressure Sensors

Conventional pressure sensors are temperature limited while SiC-based pressure sensors have a much wider temperature range. They also have the added benefit that high temperature SiC electronics can be integrated with the sensor. However, the difficulty of micromachining SiC to form a well-defined diaphragm structure, combined with the lack of reliable device packaging for these operating environments, has largely prevented the application of these devices. Progress has been made at NASA GRC in both SiC pressure sensor micromachining and packaging [3]. A SiC sensor die (2.1 x 2.1 mm^2) is mounted on an aluminum nitride (AlN) header (0.25 in. diameter) by the direct chip attach (DCA) method, as shown in Fig. 4, so that only the sensor's circular diaphragm is free to deflect in and out of the reference cavity. The design significantly limits the effect that stresses in the package can have on the sensor output.

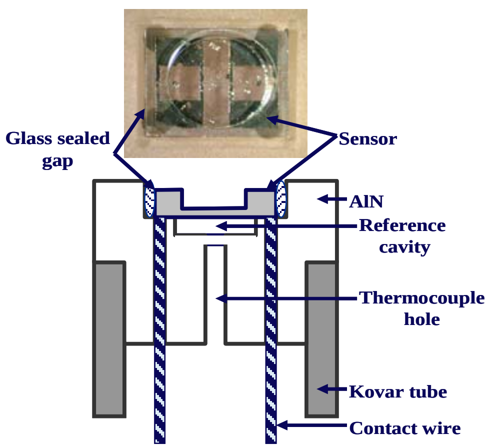

Fig. 4. Top and cross-sectional views of MEMS-DCA package featuring direct wire contact to sensor and thermocouple access hole for temperature compensation and calibration.

Fig. 5 shows the net bridge output and strain sensitivity for a typical SiC pressure sensor as a function of pressure at various temperatures. The data demonstrates the capabilities of the pressure sensor to withstand high temperatures with improved reliability. The sensor has an expanded temperature range beyond what is shown in Fig. 5, up to 600^{o}C [4]. These temperature ranges are more than adequate for Venus applications.

The high temperature operation (600^{o}C) of a SiC pressure sensor and anemometer has been previously demonstrated as separate discrete sensing devices [4]. Ongoing research effort is geared towards integrating three functionalities by the utilization of advanced SiC MEMS Microsystems technology: a pressure sensor, an anemometer, and a fully passivated resistance temperature differential sensor. [5]

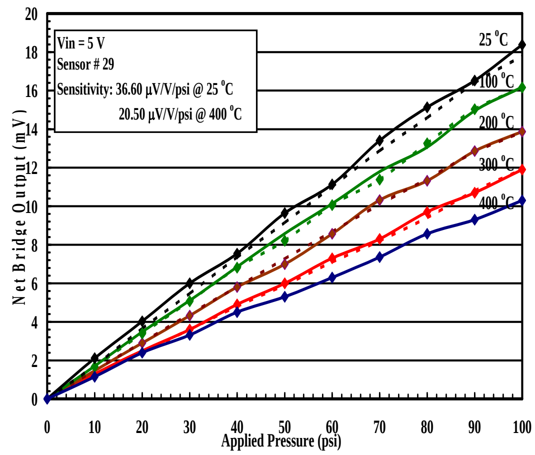

Fig. 5. Net voltage as a function of pressure for various temperatures. Solid and dashed plots represent heating and cooling excursions, respectively.

3.2 Thin Film Physical Sensors

NASA GRC has an in-house effort to develop thin film sensors for surface measurement in propulsion system research. The sensors include those for strain, temperature, heat flux, and surface flow which will enable critical vehicle health monitoring of future space and air vehicles [6,7]. The current challenges of instrumentation technology are to further develop specialized sensor systems, further develop instrumentation techniques on complex surfaces, improve sensor durability, and address needs for higher temperature applications exceeding 1000 °C. The use of sensors made of thin films has several advantages over wire or foil sensors. Thin film sensors do not require special machining of the components on which they are mounted, and with thicknesses less than 10 µm, they are considerably thinner than wire or foils. Thin film sensors are thus much less disturbing to the operating environment, and have a minimal impact on the physical characteristics of the supporting components. A broad array of thin film physical sensor technology is being developed.

One area of development is a patented thin film multifunctional sensor which integrates into one "smart" sensor the designs of individual gauges that measure strain magnitudes and direction, heat flux, surface temperature, flow speed and direction [8,9]. The entire gauge is microfabricated, enclosing a triangular area approximately 1.5 cm on a side with 50-µm-wide features, and is shown in Fig. 6. Designed for applications in material systems and engine components testing, the sensor can provide minimally intrusive characterization of advanced propulsion materials and components in hostile, high-temperature environments, validation of propulsion system design codes, and experimental verification of computational models. Various prototypes of the gauge have been bench tested on alumina substrates [9]. Future testing will include measuring all of the parameters simultaneously on a component to be tested in an engine environment. Thus, in one sensor system, a range of physical parameters regarding the immediate environment can be measured in Venus relevant environments. Further, this microsensor system can provide information on structural properties of the vehicle in the harsh Venus environment.

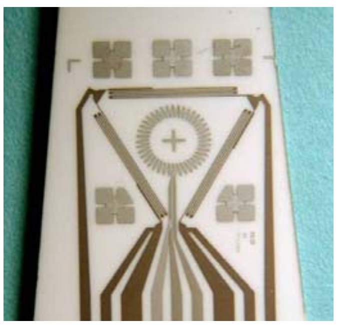

Fig. 6. A thin film multifunctional sensor in the geometry of an off-axis rosette.

3.3 Chemical Sensor Technology

The development of MEMS-based chemical microsensors to measure emissions in harsh environments has been on-going for a considerable time for emission monitoring applications [10]. The development of such a MEMS-based chemical sensors array, or High Temperature Electronic Nose, has begun using high temperature gas sensors being developed for a range of applications [10,11]. There are three very different sensor types that constitute the High Temperature Electronic Nose: resistors, electrochemical cells, and Schottky diodes. Each sensor type provides qualitatively very different types of information on the environment being monitored. This is in contrast to a conventional array of sensors that generally consists of elements of the same type, e.g., tin oxide (SnO_2) resistors doped differently for different selectivities. It is envisioned that the elements of the High Temperature Electronic Nose array (resistors, diodes, and electrochemical cells) will have very different responses to the individual gases in the environment.

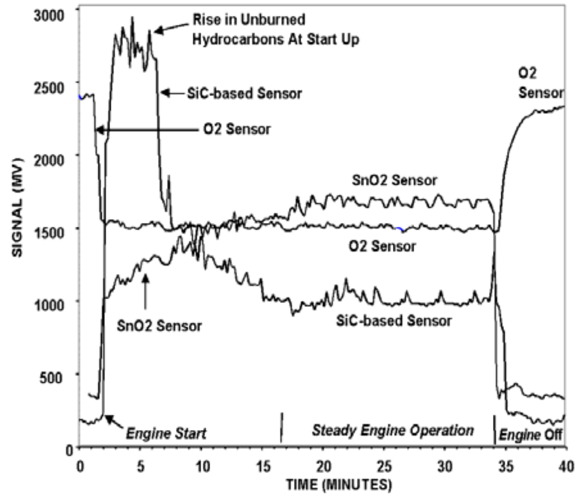

Fig. 7. The response of a sensor array composed of a tin oxide based sensor (doped for NO_x sensitivity), an oxygen sensor, and a SiC-based hydrocarbon sensor in an engine environment.

A first generation High Temperature Electronic Nose has been demonstrated on a modified automotive propulsion system. Fig. 7 shows the response of a nanocrystalline tin oxide based sensor (doped for nitrogen oxide or NO_x sensitivity), an oxygen (O_2) sensor, and a SiC-based hydrocarbon (C_xH_y) sensor. The figure shows the individual sensor responses during the initial start of the propulsion system, a warm-up period, a steady state operation period, and at the engine turn-off. The sensors were operated at 400°C while the engine operating temperature was 337°C. Each sensor has a different characteristic response. The results are qualitatively consistent with what would be expected for this type of engine. They also show the value of using sensors with very different response mechanisms in an electronic nose array: the information provided by each sensor was unique and monitored a different aspect of the engine's chemical behavior.

This data shows the capability to detect multiple chemical species in Venus relevant environments. Higher temperature operation has been achieved for some sensors and other species can be detected. Overall, a potential chemical sensor array can be tailored to measure chemical species specifically relevant for Venus applications.

4. MOBILE SENSOR PLATFORMS

Mobile sensor platforms are also being developed for sensor placement, as well as methods for communicating between roving platforms and a central command location. This work, begun in the mid 1990's, leverages commercially available equipment to miniaturize existing sensor platforms and produce mobile platforms that are planetary exploration compatible. While initially envisioned for use in engine maintenance, the major thrust of this work was to produce systems of sturdy, simple design meeting a technology gap in methods to move sensors from one location to another. These mobile sensor platforms can be integrated with a range of instrumentation as well as potential alternate modes of locomotion for planetary exploration.

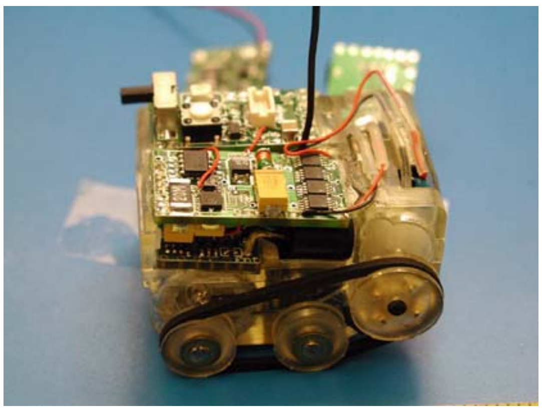

Fig. 8. Miniature Sensor Platform containing RF communications, video camera, and a temperature sensor.

In the nineties, a series of small rover initiatives were executed under aeronautics funding to look into the practicality of performing robotic inspection within airframe structures such as engines and fuel tanks. During these efforts, the technological hurdles overcome were the miniaturization of the platforms along with the embedment of sensors and communications. A sensor platform, as seen in Fig. 8, which carried two way RF communications, a video camera, and a temperature sensor and displaced less than 60 cubic centimeters was fabricated.

More recently, the Optical Instrumentation and NDE Branch at NASA GRC has been collaborating with academia to pursue other mobile sensor platform activities. A proposal under ROSES 05 titled Terrestrial and Extraterrestrial Astrobiology Science and Engineering Research Vehicles for Remote Sensing (TEA SERVERS): Advanced Mobile Sensor Platforms For Astrobiolology was submitted with Case Western Reserve University researchers and Dr. Penelope Boston of New Mexico Tech. Within this proposal, a biologically inspired walking robot named a Whegs, modeled after the common cockroach, was proposed in combination with a planetary instrumentation exploration suite (Fig. 9). It is envisioned that groups of these simple sensor platforms investigating an area of interest to scientists could add breadth of coverage to complement the activities of a larger, more heavily instrumented single large rover leading the group.

Fig. 9. Whegs Vehicle operating in uneven terrain using the locomotion approach of a cockroach (picture courtesy of Case Western Reserve University).

Fig. 10: NASA GRC Sensor Platform "Mule" for demonstrating technologies on the CMU Highlander.

Fig. 11. CMU Highlander Rover operation in simulated Lunar environments.

Most recently, a tracked "mule" or test robot (shown in Fig. 10) has been fabricated to develop and verify instrumentation, sensors, communications and control algorithms for the Carnegie Mellon University (CMU) Robotics Institute's Highlander Lunar Rover Initiative. The Highlander Lunar Rover system, shown in Fig. 11, has a range of subsystems whose operation and maturity need to be verified before operational deployment. To date, a Sterling Radioisotope Generator simulator for prototyping has been provided to CMU by GRC. Also, the Highlander is currently using GRC designed and built control and communications electronics which reside between the Highlander main CPU and the various actuators. NASA GRC has also provided the RF communications, onboard communications, the inertial measurement unit, and tilt and power monitoring sensors for the robot. The interface and control software was also developed by NASA GRC.

5. MICROSENSOR SYSTEMS

A range of Microsystems based chemical sensors have also been developed for applications such as fire detection, leak detection, EVA, and environmental monitoring. These microsensors have been demonstrated on a range of aerospace applications. This technology utilizes basic microsensor platforms that can be modified as needed for a given application. A range of gases of general planetary exploration interest can be measured including methane, ammonia, carbon dioxide, oxygen, and hydrogen.

This development also includes a "Lick and Stick" sensor package featuring sensors, power, signal conditioning, and telemetry on a near postage stamp size unit. The objective in the leak detection project is to produce a microsensor array, which includes hydrogen (H_2), O_2, and C_xH_y [10]. Thus, a range of potential launch vehicle fuels (hydrogen or hydrocarbons) and oxygen can be measured simultaneously. The array is being incorporated with signal conditioning electronics, power, data storage, and telemetry. The final system is envisioned to be self-contained with the surface area comparable to a postage stamp. Thus, this postage stamp sized "Lick and Stick" type gas sensor technology can enable a matrix of leak detection sensors placed throughout a region with minimal size and weight as well as with no power consumption from the vehicle. Sensor outputs are fed to a data processing station, enabling realtime visual images of leaks, and enhancing vehicle safety.

A prototype model of the "Lick and Stick" sensor system has been fabricated and is shown in Fig. 12 [12]. The complete system has signal conditioning electronics, power, data storage, and telemetry with hydrogen, hydrocarbon, and oxygen sensors. Fig. 13 shows the operation of the electronics plus the three sensor system simultaneously. In particular, the data highlights the response of a SiC-based hydrocarbon sensor at various hydrocarbon fuel (RP-1) concentrations. The oxygen concentration is held constant and the hydrogen sensor signal shows no response, suggesting a lack of cross-sensitivity between the hydrogen and hydrocarbon sensors to the detection of this hydrocarbon.

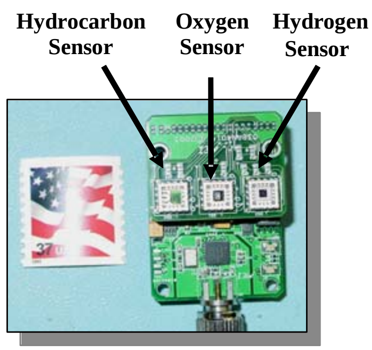

Fig. 12. A prototype version of a "Lick and Stick" leak sensor system with hydrogen, hydrocarbon, and oxygen detection capabilities combined with supporting electronics including signal conditioning and telemetry.

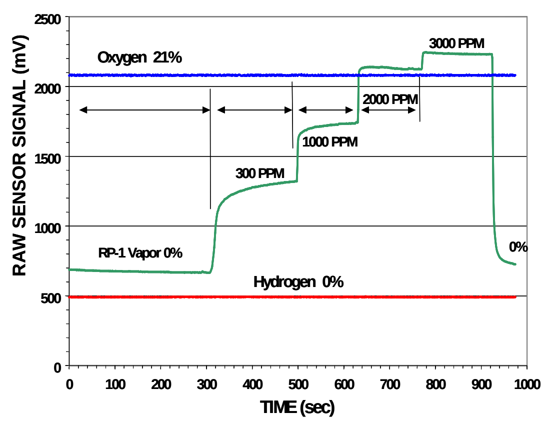

Fig. 13. Response of the three sensors of the leak sensor system to a constant oxygen environment and varying hydrocarbon (RP-1) concentrations. The sensor signal shown is the output from the signal conditioning electronics which processes the measured sensor current at a constant voltage.

Also being developed is a microfabricated particle classifier. The combination of a range of chemical species measurements with particle classification is a significant potential tool to broadly characterize a planetary surface. The approach adopted here for the measurement of particle size distributions, number density, and ambient charge state is that of ion or electrical mobility classification (IMC or EMC) [13]. The EMC process exploits differences in individual particle mobilities to perform either spatial or temporal classification. One objective of the sensor development work is the fabrication of microscale particulate detectors and classifiers [14].

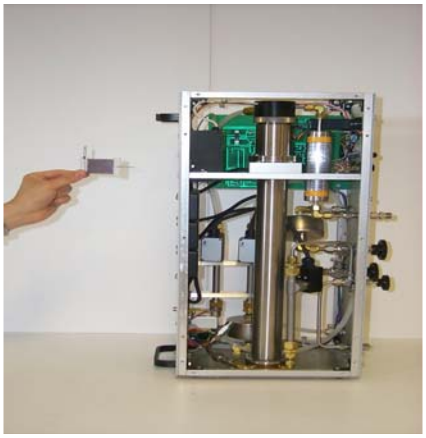

Figure 14. MEMS particulate classifier contrasted with traditional macroscale device.

A prototype MEMS particulate sensor is shown in Fig. 14. For comparison, this device is contrasted with the conventional macroscale device which it replaces. This sensor is in the form of a wafer stack, wherein the active channel is composed of a pair of silicon substrates separated by a dielectric spacer. All features of this device are fabricated using conventional thin film lithography and deposition techniques, combined with relatively standard MEMS wafer etching and micromachining methods. The combined approach of microchemical sensors and microparticulate detectors has been applied to cargo bay fire detection applications with the resulting system demonstration yielding a significantly decreased false fire alarm rate and a highly increased confidence in the measurement.

The application of these microsystems for planetary exploration would enable a broad-based instrument for understanding planetary environments and enabling the detection of the chemical signatures of life. Measuring chemical constituents of a sample should be done with as broad a simultaneous identification of as many species as feasible. The microsystem technology above provides a range of tools, from multiple chemical species to particulate analysis, to understand the planetary environment. Further, these tools are provided using Microsystems technology which minimizes size, weight, and power consumption.

6. SUMMARY AND POSSIBLE PLANETARY APPLICATIONS

This paper has presented a range of technologies which can enable planetary missions. This includes the electronics to process data and operate instruments, micro chemical and particulate sensors to measure multiple facets of the planetary environment, and mobile sensor platforms to move the electronics and sensors around a planetary environment. Harsh environment sensor technology will enable Venus missions and also monitor vehicle component conditions such as those of an engine.

A common thread associated with this electronics and instrumentation development is the enabling of small, smart, rugged, and mobile systems. Measurements at one location are likely not enough to be able to make conclusions regarding the presence of life. While it may occur that everything one needs to measure can be found at, for example, the lander's location, measurements at a variety of locations are more likely to provide a larger picture of planetary conditions as well as increase the probability of taking a measurement indicative of life. Such activities may be hampered by large, power consumptive systems.

Thus, there is a strong need for low power devices which can be mobile and provide substantial characterization of the planetary environment where and when needed. The sensors, electronics, and mobile platforms described here are uniquely capable of low power operation in relevant environments. While a given mission will require tailoring of the technology for the application, basic tools which can enable new planetary missions are being developed.

7. ACKNOWLEDGEMENTS

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